ELSEVIER

Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 15 (2014) 300 – 305

www.elsevier.com/locate/procedia

21st CIRP Conference on Life Cycle Engineering

Energy quality hierarchy and "transformity" in evaluation of product's working principles

Ida Midžić*, Mario Štorga, Dorian Marjanović

University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Ivana Lučića 5, 10002 Zagreb, Croatia

* Corresponding author. Tel.: +385-1-6168-117; fax: +385-1-6168-284. *E-mail address:* ida.midzic@fsb.hr

Abstract

Development of environmentally friendly products and solutions is becoming a major driver for innovation and product development. In the literature there is neither unified approach nor methodology to establish the ecological value of future product at conceptual level. This is particularly important in cases where new and sustainable alternatives are considered to replace well-established, but environmentally costly products and solutions. In this work a method for estimating "transformity" value of product's working principles is proposed in order to define ecological quality evaluation criteria. Research is based on assumption that "transformity" of product's working principles is also ecological quality criteria that might be used by designers for evaluating product's concept variants in early design stages of product development process.

Selection and peer-review under responsibility of the International Scientific Committee of the 21st CIRP Conference on Life Cycle Engineering in the person of the Conference Chair Prof. Terje K. Lien

Keywords: Evaluation ; Energy ; Eco-design methodology

1. Introduction

In order to establish a measure of energy quality in physical sciences, the term "transformity" was first introduced by D. M. Scienceman [1] in collaboration with H. T. Odum [2]. Transformity is a measure of energy quality [3] and is used to represent energy transformation capability or relative "ease of energy transformation" [4]. It is defined as the emergy of one type of energy to make one joule of energy of another type [5]. There are different rankings of energy quality, but most comprehensive one is Odum's, who compiled a hierarchy of energy quality based upon solar emergy units - solar transformities [5,2]. Most importantly, transformity can be used to measure the position of each kind of energy (energy form) in a universal energy hierarchy [6], thus enabling evaluation of energy quality according to ability to do work [7].

Product's working principles are used to elaborate 'how the product fulfills its function', so supply and facilitate effects to perform the desired transformation of energy, material and information [8]. When defining the desired effects, designer defines the functions of the future product in its working (operating) state [9]. For each desired effect, chain of transformations of energy, material and information can be composed. In this work, energy quality criterion for evaluating product's working principles is proposed. The premise stated is that energy transformation quality of product's working principles is also evaluation criteria of product's environmental value, thus ecological quality criteria of product's working principles.

For the purpose of estimating energy transformation quality ("transformity") of product's working principles; energy transformations performed by the product internally (from one form of energy to the other) are represented by chains of energy transformations. A single chain of energy transformations is established according to sequence of energy forms transformations required to accomplish the desired function. A proposed energy transformation evaluation criteria is created according to a hierarchical scale for ranking energy forms quality.

Selection and peer-review under responsibility of the International Scientific Committee of the 21st CIRP Conference on Life Cycle Engineering in the person of the Conference Chair Prof. Terje K. Lien
doi:10.1016/j.procir.2014.06.084

The concept of "transformity value" of product's working principles is introduced to estimate working principles' energy transformation quality and to use this measure for eco-evaluations. Transformity value is estimated when evaluating the chain of internal energy transformations required for establishing physical effects and enabling product's function and purpose. Underlying premise about transformity value is that it can then be used as evaluation criteria in conceptual design stage, since knowledge about the product at this stage is sufficient for conducting this type of estimation. In this work, transformity value as evaluation criterion is explained by using two different working principles for laundry washing and cleaning: warm water with detergent washing, and ultrasonic washing and cleaning.

2. "Transformity" - energy transformation quality

Transformity or energy transformation quality is emergy of one type of energy required to make a unit of energy of another type. It is considered to be a dimensionless ratio of emergy to available energy, thus ratio of one energy form input to a different energy form output [4,6]. Transformity can be described as the "ease of energy transformation" based upon abundance of energy forms in nature [4], so is used for evaluation of energy quality [3]. Further, transformity is used to quantify hierarchical position of each energy type (form) in a universal energy hierarchy.

Transformity and emergy are hierarchical energy concepts used when analyzing and modeling energy systems. Emergy (spelled with an 'm' and often capitalized to prevent confusion with energy) is defined as the available energy of one kind required directly and indirectly to make a product or service [5]. It is measured in emjoules. Transformities are calculated from emergy flows and measure position in an energy hierarchy. Transformity is defined as the emergy per unit energy. Units are emjoules per joule. In energy systems, energy sources and components are connected with energy flows and arranged from left to right, thus describe the order of increasing transformity. Transformities increase with successive energy transformations [5]. Concepts of emergy and transformity comply with the energy conservation law and second law of energy depreciation.

2.1. Evaluation of energy quality

There are two main methodological approaches to quantifying energy quality. Methods for calculating energy quality can be receiver or donor methods. Main distinction between the two approaches is in the assumption weather energy quality can be upgraded in the energy transformation process. In the case of energy transformity, which Odum defined to be a donor-based evaluation technique, the assumption is that upgraded energy quality has a greater capacity to feedback and control lower grades of energy quality. Energy quality here is a measure of the amount of energy used (directly and indirectly) in an energy transformation that is then used into sustaining a product or service. Donor-based approaches to energy quality consider that ability of a particular energy form to produce work is dependent not only on the form of energy, but also on the type of system that is analyzed, so first calculations of energy quality were made in units that were calories. Concepts of emergy and solar transformity were introduced afterwards and based on a number of cases where food systems, ecological systems and power systems were analyzed. For example, until then, heat measures for energy could recognize only one aspect of energy - its ability to raise the temperature of objects or matter, but were unable to adequately quantify work potential of heat used in more complex processes [7]. This line of thinking also corresponds well to Thumann who noted that essential quality of energy forms (heat in this case) is not the amount, but rather it's value [10].

2.2. Ohta's ranking of energy quality

Ohta classified five forms of energy. He considers quality of energy as relative ease of energy transformation from one form to the other. 'If energy A is relatively easier to convert to energy B but energy B is relatively harder to convert to energy A, then the quality of energy A is defined as being higher than that of B' [3]. Ohta's ranking of energy quality is also based upon abundance of different energy forms in nature. For example, electric energy is not included in the hierarchy, because electrical energy is rarely present in nature. Electrical energy can be found in form of electrical discharge in bad weather conditions (lightning), so as such is rarely available in nature. Further, Ohta states that conversion between mechanical energy and electrical energy is achieved with very high efficiency, thus electromagnetic energy is ranked first, followed by mechanical energy.

Ohta's hierarchical rank of energy form quality	
Electromagnetic	Highest quality
Mechanical	↑
Photon	
Chemical	
Heat	Lowest quality

Fig. 1. Ohta's ranking of energy form quality [4]

2.3. Solar transformities and Odum's hierarchy of energy quality

Odum's approach to transformity is based upon embodied solar energy equivalence of energy form (Table 1). This allowed Odum to establish comparable transformity units, thus solar transformity of various energy forms and compile a hierarchy of energy quality based upon solar transformities calculated (Figure 2).

Odum's hierarchy of energy quality is composed according to comparable embodied solar energy equivalence to energy form transformation units (solar emjoules per joule). Through transformity, different types, levels and not comparative energy forms are converted into the same measurement standard – emergy, which provides a uniform platform to evaluate the products and services quantitatively [7].

Table 1. Odum's solar transformities [2]

Energy form	Solar transformities (solar emjoules per joule), sej/J
Sunlight	1
Wind kinetic energy	623
Unconsolidated organic matter	4 420
Geopotential energy in dispersed rain	8 888
Chemical energy in dispersed rain	15 423
Geopotential energy in rivers	23 564
Chemical energy in rivers	41 000
Mechanical energy, waves, tides	17 000 - 29 000
Consolidated fuel	18 000 - 58 000
Food, greens, grain, staples	24 000 - 200 000
Protein foods	1 000 000 - 4 000 000
Human services	80 000 - 5 000 000 000
Information	10 000 - 10 000 000 000 000

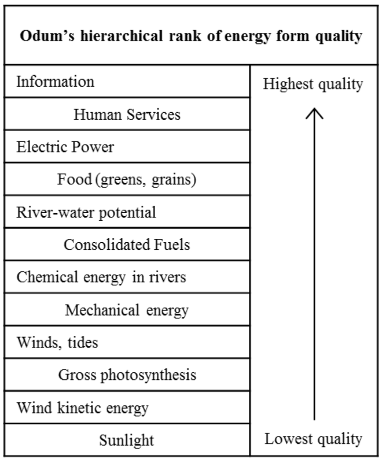

Fig. 2. Hierarchical rank of energy form quality according to Odum [2]

3. Product's working principles

According to theory of technical systems, purpose of the product is represented by the system of its output effects to the technical process [9]. Working principles describe how the product fulfills its function and which physical effects to be delivered by the product (technical system). Working principles are further decomposed to solution principles recognized as being suitable for delivering desired functions and effects, where effects are defined by physical laws and properties (material and geometrical properties).

3.1. Conceptual design stage of product development process

Early stages of product development process are characterized by low level of product concretization and description, and not all aspects of product's life cycle can be specified previous to embodiment and detailing [11]. In conceptual design stage, product's functions, working principles and product's structure is defined. Main goal of the concept development is to define the structure of the future product. Usually several concepts are developed and most appropriate one is selected for further development. After a series of iterations between concept formulation and evaluation has yielded one or more desirable concepts, the process enters the embodiment design stage and after that, the detailing design stage. Functions, working principles, effects and principle solutions are used to formulate and elaborate product's concepts [12].

3.2. Technical system's internal transformations

According to the theory of technical systems, product systems are transformation systems. Theoretical foundations of the theory are used to explain the relations between product's working principles and effects, and how the chains of energy, material and information transformation are composed. Transformation system is a system of operators that transforms an operand through a technical process from an existing state to a desired state. There are three kinds of operators that provide effects on the transformation process: human systems, technical systems and active environments [9]. Effects posed on the transformation system can be described as material, energy or information, or any combination of those. They are caused by the change of state of operands, and for this change to happen, it has to be supported by one or more effects (due to again some other transformation process). Effect is defined as physical, chemical, or biological law, relation or phenomenon with which a desired function can be performed [8]. Functions describe the capability of the technical system to deliver necessary effects. Working principles describe how necessary effects are going to be accomplished by the technical system (product), and their embodiment is further described by solution principles.

Energy form transformations defined by working principles, principle solutions and effects are represented by chains of energy, material and information transformations [13]. Each chain consists of intermediate effects describing the transformations of energy, material and information (necessary effects) for acquiring the desired effect.

4. "Transformity" value of product's working principles

4.1. Composition of energy form quality hierarchy for evaluation of product's working principles

Transformity or energy transformation quality is used to quantify hierarchical position of each energy type (form) in a universal energy hierarchy. Odum's hierarchy of energy quality (Figure 2) is composed according to comparable embodied solar energy equivalence to energy form transformation units (solar emjoules per joule). Hierarchy of energy quality used for evaluations of chains of internal technical system's transformations for acquiring the desired physical effects is combined from two hierarchical ranks of energy form quality. Since Ohta's (Figure 1) and Odum's (Figure 2) hierarchies are complementary, a combined hierarchy of energy forms for transformity estimation is composed. Energy forms are ranked in a hierarchical way as illustrated in Figure 3.

Hierarchical rank of energy (energy type or form) quality	Direction of transformations of energy forms to gain higher energy quality is low to high quality. If we try to attain some energy forms from high quality to lower quality energy form, then we waste higher quality energy forms on attaining lower energy forms, so those transformations are of lower transformity value (score).	Transformity value (score) for each energy form in the hieararchy	Scores for each energy form
Information	Highest quality	1 000 000 000 000 000	10 ^ 15
Human Services	↑	1 000 000 000 000	10 ^ 12
Electric Power		10 000 000 000	10 ^ 10
Food (greens, grains)			
Electromagnetic energy			
River-water potential			
Consolidated Fuels		10 000 000	10 ^ 7
Chemical energy in rivers			
Mechanical energy		100 000	10 ^ 5
Winds, tides			
Gross photosynthesis, photon energy			
Chemical energy		100	10 ^ 2
Heat		10	10 ^ 1
Wind kinetic energy			
Sunlight	Lowest quality	1	1

Fig. 3. Hierarchical rank of energy form quality and transformity scores for each energy form quality rank (level). Hierarchy of energy form quality is used for evaluating chains of energy form transformations for requiring desired physical effects (working principles of the product)

Each energy quality (transformity) level is assigned with a value representing the value of the energy quality level. Logarithmic scale that is used for assigning values to energy quality levels is used in calculations of natural phenomena [14]. Also, performing calculations with common base-10 logarithms does not require difficult computations.

4.2. Proposed method for calculating product's working principles' "transformity value" and example

Proposed procedure for estimating working principles' transformity value is described in a small example. Working principles of two concept variants are compared. First concept variant is conventional laundry washing concept implemented in most washing machines on the market and in households. Conventional washing machines use hot water, detergent and electrical energy to acquire centrifugal force for washing, cleaning and agitating laundry fibers. Second variant is ultrasonic washing machine concept. The difference from the first concept is that ultrasonic cleaning performs laundry agitation, e.g. cavitation effect is used to remove the dirt from the fibers and without damaging the fibers.

Working principles need to be decomposed to acquire chains of physical effects described by physical laws, so intermediate energy form transformations could be identified and transformity value calculated. Each energy form transformation to another energy form is evaluated in the following way. The score of a particular energy form level (Figure 3) is multiplied with or divided by (depending on higher or lower position of desired energy form) score distance according to the hierarchy. Transformations in which energy form is not changed (as is the case with 'Heat' in Figure 4 and 'Mechanical energy' in Figure 5) are assigned with energy quality level score and added to the total. Accumulated score is then the total score for a single chain (which ends with desired physical effect, e.g. energy form).

Chain of physical laws (intermediate effects or energy transformations) for acquiring the desired effect:

U → Q → Q

$U = I*R$; $Q = I^2*R*t$; $Q = \alpha*A*(T_1-T_2)$

Substituting physical laws with its suitable energy forms in the transformation chain:

Electrical energy → **Heat** → **Heat**

Scoring procedure:

10^10 divided by 10^10 adding 10^1

(since there is a negative leap to 10^1 transformity level) (since there is no change of the transformity level)

Transformity value score for a single chain: 11.

Fig. 4. Example of transformation value calculation for transformation of electrical energy into heat (water heating effect)

Chain of energy forms transformations for acquiring the desired effect (centrifugal force):

Electrical energy → **Mechanical energy** → **Mechanical energy**

Scoring procedure:

10^10 divided by 10^6 adding 10^5

(since there is a negative leap to 10^5 transformity level) (since there is no change of the transformity level)

Transformity value score for a single chain: 110 000.

Fig. 5. Example of transformity value calculation for transformation of electrical energy into mechanical energy (agitation of laundry by centrifugal force)

Chain of energy forms transformations for acquiring the desired effects of cavitation effect joined with chain of transformations of energy for for distributing water (theoretically):

Electrical energy → **Mechanical energy** → **River-water potential**

Scoring procedure:

10^10 divided by 10^6 multiplied with 10^3

(since there is a negative leap to 10^5 transformity level) (since there is a positive leap to 10^6 transformity level)

Transformity value score for two chains (theoretically): 10 000 000.

Fig. 6. An example of transformity value calculation for two transformation chains (theoretical assumption)

4.3. Comparison of "transformity value" scores and elaboration of results

Energy form quality hierarchy scale is used for establishing transformity value (energy quality level) and criteria for evaluation of product's working principles (Figure 3). Chains of internal energy form transformations represent transformations of energy forms. Transformation energy form quality (energy form A to energy form B) is evaluated according to hierarchical ranking of energy form quality and transformity value is estimated according to a scoring system demonstrated in an example (Figure 4, 5 and 6).

According to a revised maximum power hypothesis about maximizing useful emergy flow (emjoules per time), alternatives with higher transformity are more desirable [5]. Inspired by that claim, chains with higher transformity value are considered to be more desirable alternatives to requiring the desired effects. Transformity measures position in the universal energy hierarchy, and transformity value increases with every additional energy transformation, if the direction of the transformation is lower to higher energy transformity level (lower to higher energy quality). On the contrary, if higher energy forms are transformed into lower energy forms, higher quality energy forms are wasted on obtaining lower quality energy forms, and thus transformity value is reciprocal.

5. Discussion

5.1. Motivation for establishing ecological quality criteria

Recent trends and increase in interest in eco-innovation often emphasized by product developers, companies and customers alike, point out that developing environmentally friendly products and solutions is becoming a major driver for innovation and product development in general. Due to complexity of product development, opportunities for developing products with less emission, waste and generally reduced environmental impact can easily be missed if design objectives are not handled properly and in as earlier design development stages. Early design stages are often described as decisive because decisions taken in early design stages have a higher effect on the final outcome compared to decisions at the end of the design process [15]. Contradiction here is that there is less knowledge about the product in early design stages, but still decisions taken have more impact or effect to final product, its features, structure and form. Thus, possibly, there is abundance of opportunities for developing environmentally friendly products starting from early stages of development process.

Environmental or eco-value of products developed, for engineers and designers is closely related to product's environmental impact, product's 'fitness for life' and life cycle performance. Environmental impacts point out to the level of 'environmental friendliness' of products [16]. It is broadly considered that environmental impact assessment is the only method available to measure the impact of products on the environment [17]. Technically, product's environmental value can only be measured in environmental impact units, and most methods that are environmental impact assessment methods are quantitative. Environmental impact assessment is an analysis of product's life cycle and material and energy flows concerning material acquisition, production, use and end-of-life. In most cases, knowledge about the product and its life cycle in early design stages is not sufficient for conducting environmental impact assessment [13]. Since environmental impact assessment is primarily a quantitative method, objective of the presented research is to establish qualitative eco-value evaluation criteria more suitable for early design and product concept evaluation.

Eco-efficiency is also used as a measure of environmental performance of the product. Here, environmental value of the product is a ratio usually of product's value expressed in monetary units and environmental load expressed in environmental impact. However, as implied by Straton, the concept of value (ecological value) is rather to be associated to capacity (capacity to contribute to value) and quality (measurable in some objective evaluation unit) [18].

Recent research studies related to products and their environmental impact are focused at establishing groups of products with similar environmental impact and life cycle characteristics [19,20,21,22]. Identified product groups are created by combining results of life cycle analysis for about 60 to 150 product cases per research. Products with similar environmental profile, environmental impacts and dominant life cycle phase are grouped together, so similar product properties, attributes, working principle and life cycle characteristics can be identified for each product group or category. Consequentially, models could be proposed aiming at early simulation of environmental impacts for specific products within the group.

Identifying product groups mostly allow designers to classify products into their suitable group and thus distinguish products according to dominant life cycle phase. On most basic categorization level, products can be divided in two product groups: use intensive and material intensive products. For products with more material intensive environmental impact - it is considered that material acquisition phase, product's structure and embodiment have a much bigger impact in overall environmental impact of the product. According to dominant life cycle phase, domestic appliances, vehicles, office machinery fall in the category of intensive products, where the most environmental damage is caused in use life cycle phase [23]. These products consume not only energy, but also other materials, and water (e.g. besides electric energy, washing machines consume detergent, additives and large amounts of water). Energy and material consumption are most important when intensive product's use phase is considered. Assumption is that environmental value of such products is mostly dependent upon its performance in use phase, but also dependent upon working principles, thus how the product fulfills its function, which effects to deliver and by which means (solution principles).

5.2. Limitations of proposed method

Method for estimating transformity value of product's working principles is proposed. The limitations that need to be considered regarding the purpose and use of the proposed method are as follows:

1. Limitation regarding using the method for evaluating transformity of working principles for product's with energy-using and use intensive products

Due to findings about product types and groups concerning their intensive life cycle phase, the recommendation is that the method is not suitable for evaluating transformity of material intensive products. This issue can be resolved by including a similar hierarchical rank for evaluating transformations of materials, not just energy form quality evaluations. Therefore, transformity of material inputs would be evaluated according to change of state of the matter (material inputs that are transformed in the transformation process to accomplish desired effects).

2. Problems with identifying latent and side effects at this design stage to include them in transformity value calculations

When defining the duties of the technical system and establishing principle solutions, there are two types of effects to consider. Active effects have direct, immediate effect on the environment, thus prediction of this effects through a systematic design is foreseeable. Passive effects with delayed effect on environment are built in features of technical system. Those environmental effects are latent through the life cycle of technical system and therefore not easy to predict. The direct environmental effects are stems from desired outputs of technical system, while indirect environmental effects arise from secondary outputs. Desired outputs (effects) conform to the technology chosen for transformation of operand in the technical process [13]. To establish secondary, undesired, latent and side effects or outputs, additional methods need to be employed, and thus are not included in evaluation of working principles' transformity value as proposed in this work.

6. Conclusion

The concept of "transformity" of product's working principles is presented in this work. "Transformity" or energy transformation quality is a measure of energy transformation quality [2,3] or "relative ease of energy transformation" [4]. It is a way of representing energy form quality to evaluate its position in the universal energy hierarchy. The method proposed in this work is to be used for calculating transformity value of product's working principles, e.g. transformity value of chains of internal energy form transformations. Chains of energy form transformations represent the sequence of energy form transformations to realize desired function of the product (technical system).

Proposed transformity value method is to be used for evaluation of product's working principles and comparison of its variants in conceptual design stage of product development. Premise stated in this work is that transformity value or energy form transformation quality is also ecological quality criteria, so can be used for evaluation of product concept variants. This would allow for early estimation of environmental value of product concept variants, and also comparison of concepts that are requirement compliant, with the same overall product function and purpose, but significantly differ in their functions, working principles, physical effects and principle solutions. Future work is oriented towards establishing material transformation quality (material transformity) to complete ecological quality criteria for product concept evaluation and comparison purposes.

References

[1] Scienceman, D. M., 1987. Energy and Emergy, Environmental Economics: The Analysis of a Major Interface, Pillet, G., Murota, T. (Eds.), Geneva: R. Leimgruber, p. 257-276.
[2] Odum, H. T., 1988. Self-Organization, Transformity, and Information, Science, Vol. 242, p. 1132–1139.
[3] Jørgensen, S. E., Fath, B. D., Bastianoni, S., Marques, J. C., Muller, F., Nielsen, S. N., et al., 2007. A New Ecology: Systems Perspective, Elsevier, Oxford.
[4] Ohta, T., 1994. Energy Technology: Sources, Systems and Frontier Conversion, Pergamon, Elsevier, Great Britain.
[5] Odum, H. T., Peterson, N., 1996. Simulation and evaluation with energy systems blocks, Ecological Modelling 93, p. 155-173.
[6] Brown, M. T., Odum, H. T., Jørgensen, S. E., 2004. Energy hierarchy and transformity in the universe, Ecological Modelling 178, p. 17–28.
[7] Brown, M. T., Ulgiati, S., 2004. Energy quality, emergy, and transformity: H.T. Odum's contributions to quantifying and understanding systems, Ecological Modelling 178, Issue 1-2, p. 201-213.
[8] Wilhelms, S., 2005. Function- and constraint- based conceptual design support using exchangeable, reusable principle solution elements, Artificial Intelligence for Engineering Design, Analysis and Manufacturing 19, Cambridge University Press, USA, p. 201–219.
[9] Hubka, V., Eder W. E., 2002. Theory of technical systems and engineering design synthesis, Engineering Design Synthesis: Understanding, Approaches and Tools, Chakrabarti, A. (Ed.), Springer-Verlag London Limited, p. 49–66.
[10] Thumann, A., Mehta, D. P., 2001. Handbook of energy engineering – 5th ed., Prentice-Hall, Inc., The Fairmont Press, Inc., ISBN 0-88173-347-4.
[11] Duflou, J., Dewulf, W., Sas, P., Vanherck, P., 2003. Pro-active Life Cycle Engineering Support Tools, CIRP Annals - Manufacturing Technology, vol. 52, no. 1, p. 29–32.
[12] Brunetti, G., Golob, B., 2000. A feature-based approach towards an integrated product model including conceptual design information, Computer-Aided Design 32, Elsevier, p. 877–887.
[13] Midžić, I., Marjanović, D., 2013. Environmental effects in early design stages, Proceedings of the 5th International Congress of International Association of Societies of Design Research, Tokyo, Japan, p. 840-851.
[14] Coburn, J., 2007. Precalculus, 1st Edition, McGraw-Hill Higher Education, ISBN: 0000013997.
[15] Derelöv, M., 2009. On Evaluation of Design Concepts-Modelling Approaches for Enhancing the Understanding of Design Solutions, Doctoral dissertation, Department of Management and Engineering, Linköping studies in science and technology, Linköping, Sweden.
[16] Collado-Ruiz, D., Ostad-Ahmad-Ghorabi, H., 2011. Influence of Environmental Information on Expert-perceived Creativity and Ideas, Design Creativity 2010, Taura, T., Nagai, Y. (Eds.), Springer-Verlag London Limited.
[17] Bevilacqua, M., Ciarapica, F. E., Giacchetta, G., 2012. Design for Environment as a Tool for the Development of a Sustainable Supply Chain, Springer Verlag London Limited.
[18] Straton, A., 2006. A complex systems approach to the value of ecological resources, Ecological Economics 56, p. 402-411.
[19] Andriankaja, H., Bertoluci, G., Millet, D., 2013. Development and integration of a simplified environmental assessment tool based on an environmental categorisation per range of products, Journal of Engineering Design, 24:1, p. 1-24.
[20] Collado-Ruiz, D., Ostad-Ahmad-Ghorabi, H., 2010. Comparing LCA results out of competing products: developing reference ranges from a product family approach, Journal of Cleaner Production 18, p. 355-364.
[21] Soriano, V. J., 2004. A simplified assessment methodology to environmentally-sound product design, Proceedings of the Fifth Asia Pacific Industrial Engineering and Management Systems Conference.
[22] Sousa, I., Wallace, D., 2006. Product classification to support approximate life-cycle assessment of design concepts, Technological Forecasting & Social Change 73, p. 228-249.
[23] Bârsan, L., Bârsan, A., Paralika, M., 2009. Considerations about Reducing the Environmental Impact in the Product Using Stage, Inter-eng 2009, Scientific Bulletin of the Petru Maior University of Tirgu Mures, Vol. 6 (XXIII), ISSN 1841-9267.